

determined which planetary configurations direct that trail into Earth's path, it is possible to forecast a meteor outburst of the type caused by the dust trail of long-period comets. Typically, that happens only once or twice every 60 years. No new outburst associated with long-period comets was detected with certainty this year.

Work also progressed on studies of the outbursts caused by Jupiter- and Halley-type comets; all three outbursts this year were of those types. They were observed with a mobile photographic and video camera system, tracking the orbits of individual meteoroids, determining their grain morphologies, and measuring the particle-size distribution. Those results revealed that planetary perturbations play a role in the dispersion of cometary ejecta at a very early stage.

Solar System Dynamics

Jack J. Lissauer

Progress has been made on several theoretical problems related to the dynamical structure of the solar system. Models of the early phases of the growth of solid planetary embryos on eccentric orbits were developed and used to calculate accretion rates and the accumulation of rotational angular momentum. It was found that eccentricities of the magnitude believed to be present during this period modify planetary growth rates and angular momentum accumulation only slightly, relative to the case of planets on circular orbits.

The torque exerted by a satellite on a particulate annulus centered at a mean-motion resonance was studied by using both analytic and numerical techniques. In the linear approximation, the net torque on the disk is the same as that exerted on fluid disks (which were studied previously by P. Goldreich, California Institute of Technology, Pasadena, California, and S. Tremaine, Princeton University, Princeton, New Jersey). The width of the annulus over which the bulk of the torque is exerted shrinks as time increases. The torque in a nondissipative disk is limited in time by nonlinear effects of the interaction close to resonance, which require a few thousand orbits to develop for typical solar system

A surprising discovery came from similar observations of a well known annual stream, the Quadrantids. The results revealed structure in the distribution of orbits, implying ejecta less than 500 years ago. This stream turned out to have more in common with meteor outbursts than with annual shower activity. The stream does not originate from comet 96P/Machholz 1, as was thought before. Rather, the source may be hiding as an asteroid-like object in a high-inclination orbit.

Point of Contact: P. Jenniskens
(650) 604-3086
peter@max.arc.nasa.gov

parameters. The same torque is obtained for disks of particles initially on circular orbits as for disks of particles on moderately eccentric orbits with periaapses uniformly distributed in longitude. Results of these simulations are applicable to low-optical-depth planetary rings, such as Neptune's Adams Ring, and to planetesimals within the protoplanetary disks.

Systems of planets with orbits initially identical to subsets of the planets within our solar system were integrated for very long periods of time (billions to tens of billions of years) with the Sun's mass decreased relative to the masses of the planets. Systems based on the giant planets show an approximate power-law correlation between the time elapsed until a pair of planetary orbits cross and the solar-to-planetary mass ratio, provided that this ratio is less than 0.4 times its current value. However, deviations from this relationship at larger ratios suggest that this correlation cannot be extrapolated to accurately predict the lifetime of the current system. Detailed simulations of the evolution of planetary orbits through the Sun's postmain-sequence mass-loss epoch suggest that the orbits of those terrestrial

planets that survive the Sun's red giant phase are likely to remain stable for longer than a billion years (possibly much longer), and those of the Jovian planets are likely to remain stable for more than 10 billion years (possibly much longer). Pluto is likely to escape from its current 2:3 mean-motion resonance with Neptune within a few billion years beyond the Sun's main-sequence lifetime if subject only to gravitational forces; its prognosis is even

poorer when nongravitational forces are included. Higher mass stars, which lose a larger fraction of their mass during their red giant phase, may lose their planetary systems as a consequence of their mass loss.

Point of Contact: J. Lissauer
(650) 604-2293
lissauer@ringside.arc.nasa.gov

Virtual Reality on Mars Pathfinder

C. Stoker, T. Blackmon, M. Sims, E. Zbinden

The objective of this project was to produce a three-dimensional (3-D) photo-realistic virtual reality (VR) model of the Martian surface for use in the Mars Pathfinder mission. Marsmap, the interactive terrain visualization system, creates and renders digital terrain models produced from stereo images of Mars' surface taken by the lander's images for Mars Pathfinder (IMP) camera. A primary benefit of using VR to display geologic information is that it provides an improved perception of depth and spatial layout of the remote site. The VR aspect of the display allows an operator to move freely in the environment, unconstrained by the physical limitations of the perspective from which the data were acquired. Virtual reality also offers a way to archive and retrieve information in a way that is easily understood. Combining the VR models with stereo display systems can enable a feeling of presence at the remote location. The capability, implemented in Marsmap, to interactively perform measurements from within the VR model, offered unprecedented ease in performing operations that are normally time consuming and difficult using standard photogrammetric techniques. This ground-breaking project demonstrated the power of using VR as a cartographic tool.

In the rapid production of digital terrain models (DTMs), a computational algorithm called the "stereo pipeline" was used. The core component of the stereo pipeline is the automatic matching of features in the left-eye camera image with the same features

in the right-eye camera image, thus providing the necessary correspondence to compute a 3-D location for the feature. A significant aspect of the project was the rapid production and display of models by using a distributed production team and fast data transfer. The first complete stereo panorama sequence taken after deployment of the IMP, known as the "Monster Pan," was composed of 98 stereo pairs. These data were displayed in VR at mission control at the Jet Propulsion Laboratory within 1 hour of downlink.

The Pathfinder DTMs were displayed with an interactive user interface called MarsMap which includes the following key features: (1) real-time, interactive navigation of the virtual viewpoint through the 3-D model of the landing site; (2) measurement of topographical features, including 3-D positions, distances, and angles; (3) display of daily traverses of Sojourner; (4) display of rover images within the VR model projected from the viewpoint of the rover; and (5) catalog and display of the sequence and location of science experiments conducted by the rover.

MarsMap was designed to be accessed with a standard 2-D mouse and used pull-down menus to call features. Models could be viewed in stereo using Stereographics Crystal Eyes liquid crystal display shutter glasses or with a set of head-tracked "Virtual Binoculars." The two figures show example views of the Martian surface generated using MarsMap.